

Tunneling Spectroscopy in Vertically Coupled Quantum Wires

by M. P. Lilly, E. Bielejec, J. L. Reno, and S. K. Lyo

Motivation—Tunneling measurements provide a tool to directly measure the density of states and the impact of Coulomb interactions both within and between low dimensional systems. Interpretation for two-dimensional (2D) systems is well defined in the Fermi liquid framework. Our group has focused on extending tunneling measurements to one-dimensional (1D) quantum wires. In 1D systems there remains an open question about the use of non-interacting theory to describe the tunneling and modifications due to interactions.

Accomplishment—We have measured tunneling spectroscopy in both 2D and 1D systems and compared the results to a non-interacting theory for tunneling. In 2D, differential conductance results are shown in Fig. 1a. The energy and momentum dependence of the tunneling events are captured using a voltage between the layers and an in-plane magnetic field. Qualitatively, the “fish” shape is well described by a theory for non-interacting electrons shown in Fig. 1b; interaction effects are subtle. The main features are due to overlap of the Fermi surface with the dispersion curves in the other layer. To measure 1D tunneling, we fabricated a vertical double quantum wire (Fig. 2a)¹. The 1D density is directly controlled in each wire using the split gates. Independent contact to each wire is achieved using the depletion gates. In Figs. 2b and 2c tunneling spectra are shown for 1D densities chosen such that a single subband (2b) or two subbands (2c) are occupied in each wire. The effect of increasing the number of subbands is to nest the “fish” structure, and this nesting is clearly observed at high magnetic fields where a

single crossing is observed for one subband (2b, $B=3.5$ T), and two crossings are observed for two subbands (2c, $B=3.5$ T and 4.0T). While some qualitative comparison to tunneling theory for non-interacting electrons is successful, we note a number of deviations, as well. Most significantly, the structure at low fields for a single 1D subband (Fig. 2b) is more complicated than that observed for 2D tunneling (Fig. 1a). We also observe broad resonant features at all 1D densities when a much more narrow and well defined resonance is expected. To further our understanding of the deviations, we are considering finite size effects and the role of many-body Coulomb interactions in the double quantum wire system.

Significance—1D tunneling in a split-gate-defined double quantum wire is measured for the first time. The split gate provides explicit control over the density and number of occupied subbands in each wire. The experimental tunneling spectroscopy for the 2D system is in good agreement with theory, and provides a demonstration of the technique. A number of features in the 1D spectroscopy can be clearly explained using a non-interacting picture for the electrons, but other features (broad resonance, structure in 1,1) cannot be so easily understood. Interactions within and between the wires is one possible explanation. The techniques used to create this interacting nanoelectronic structure can easily be used to fabricate a wide range of nanoelectronic systems for further studies of interactions at the nanoscale, coherent transport, single charge and spin measurement and quantum computing.

¹E. Bielejec, J. A. Seamons, J. L. Reno, and M. P. Lilly, Appl. Phys. Lett. **86**, 83101 (2005).

Sponsors for various phases of this work include: DOE Office of Basic Energy Sciences and Laboratory Directed Research & Development

Contact: Michael P. Lilly, Semiconductor Material & Device Sciences, Dept. 1123
Phone: (505) 844-4395, Fax: (505) 844-1197, E-mail: mplilly@sandia.gov

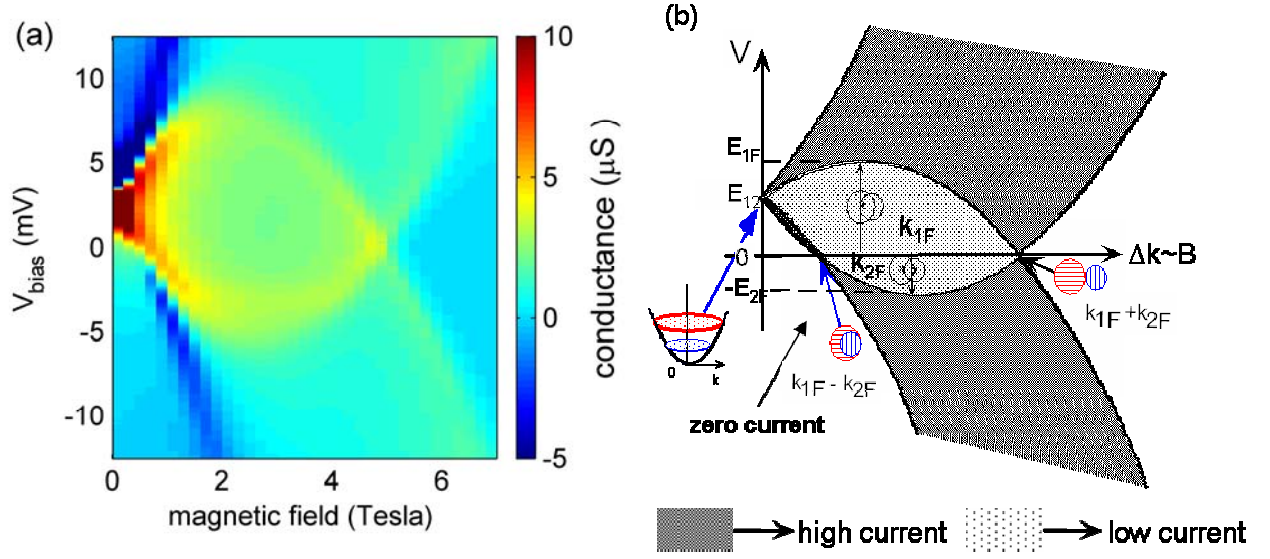


Figure 1. (a). Tunneling conductance (dI/dV) between 2D layers at $T=0.3$ K separated by a 10 nm barrier. The 2D densities are $n_1=1.96 \times 10^{11} \text{ cm}^{-2}$ and $n_2=1.16 \times 10^{11} \text{ cm}^{-2}$. (b). Theory for tunneling in a non-interacting system. Diagrams indicate relative positions of the dispersion curves. Energy difference is the y-axis in each plot, and the wave vector difference (proportional to the in-plane magnetic field) is the x-axis. The features present in the experiment are well described by the theory.

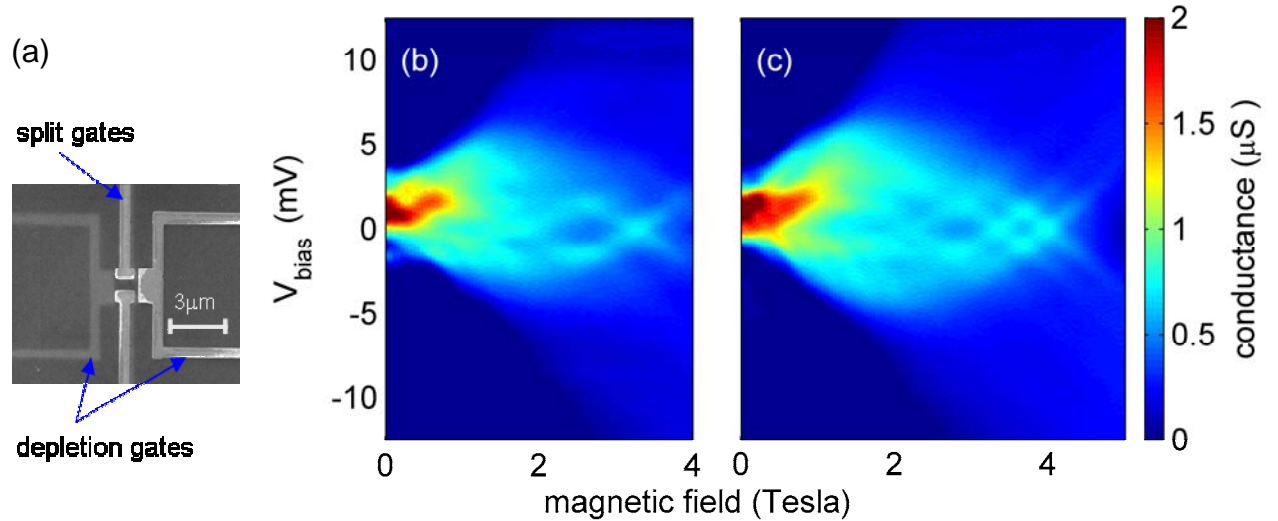


Figure 2. (a) SEM of a double quantum wire device. (b,c) Tunneling conductance for two quantum wires at $T=30\text{mK}$ separated by a 7.5 nm barrier. In (b), a single 1D subband is occupied in each wire. In (c), two subbands are occupied. The non-interacting theory in Fig. 1 can account for some features, such as the crossings at high fields [1 in (b), and 2 in (c)] but cannot account for the additional complication at low magnetic fields.